

Measuring Di-Higgs Physics via the $t\bar{t}hh \rightarrow t\bar{t}b\bar{b}b\bar{b}$ Channel

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The measurement of di-Higgs physics can provide crucial information on electroweak phase transition in the early Universe and significant clues on new physics coupling with the Higgs field directly. This measurement has been suggested to be pursued mainly via the $pp \rightarrow hh$ production. In this letter, we propose a new strategy to do that, i.e., via the $pp \rightarrow t\bar{t}hh$ production. Because of its positive correlation with the rescaled tri-Higgs coupling $\frac{\lambda}{\lambda_{\text{SM}}}$ (in comparison to a negative one for the $pp \rightarrow hh$ production) in the neighborhood of $\frac{\lambda}{\lambda_{\text{SM}}} \sim 1$, the $pp \rightarrow t\bar{t}hh$ production complements the $pp \rightarrow hh$ one in measuring di-Higgs physics, particularly for $\frac{\lambda}{\lambda_{\text{SM}}} > 1$, at both the High Luminosity LHC (HL-LHC) and a next-generation pp -collider. As an illustration, we work on the process $pp \rightarrow t\bar{t}hh \rightarrow t\bar{t}b\bar{b}b\bar{b}$. We show that a statistical significance of $> 2.0\sigma$ at the HL-LHC, comparable to that of the $pp \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$ channel, and a statistical significance of $\sim 5\sigma$ at a 100 TeV pp -collider, with 3000 fb^{-1} of data, are achievable in searching for the di-Higgs production with $\frac{\lambda}{\lambda_{\text{SM}}} = 1$.

INTRODUCTION

The measurement of di-Higgs physics plays an important role in particle physics and cosmology. In the standard model (SM) of particle physics, the Higgs field induces electroweak (EW) phase transition (EWPT) as an order parameter, by interacting with itself, while the measurement of di-Higgs physics can provide information in this regard, given the involvement of the tri-Higgs coupling λ in the di-Higgs production.

This may have important implications in cosmology. As is well known, if the EWPT is of strong enough first order, the cosmic baryon asymmetry (CBA) could be generated via EW baryogenesis. In the SM, however, such an EWPT requires a Higgs boson much lighter than 125 GeV, and hence can not be achieved without violating the current experimental bounds. To achieve this goal, several mechanisms were introduced in the SM extensions: (1) by introducing loop-corrections mediated by new scalar particles to the effective Higgs potential; (2) by incorporating nonrenormalizable operators such as $\frac{|H|^6}{\Lambda^2}$ in the effective Higgs potential; and (3) by mixing the Higgs field with a singlet scalar at tree level. No matter in which case, there is a strong correlation between the EWPT dynamics and the tri-Higgs coupling. As being pointed out in [1], at zero temperature, the tri-Higgs coupling favored by the mechanisms (1) and (2) could be a couple of times larger than its SM value λ_{SM} , while the tri-Higgs coupling favored by the mechanism (3) could be as small as $\sim 0.1\lambda_{\text{SM}}$.

In addition to the tri-Higgs coupling, the di-Higgs production may receive contributions from new physics coupling with the Higgs field. The anomalous Higgs-top operator $\frac{t\bar{t}hh}{\Lambda}$ is such an example, which often arises in the little Higgs or the composite Higgs models by integrating out a heavy top partner [2, 3]. With an insertion into the gluon fusion loop, this operator can significantly modify

the di-Higgs physics [4–6]. The measurement of di-Higgs physics therefore provides a nice tool to probe both the EWPT and new physics coupling with the Higgs field.

Because of this, the discovery of the Higgs boson in 2012 [7, 8] immediately motivated a series of studies on the measurement of di-Higgs physics at Large Hadron Collider (LHC) and High Luminosity LHC (HL-LHC) at which 300 fb^{-1} and 3000 fb^{-1} of data are expected to be collected at each of the ATLAS and the CMS detectors, respectively [9–15], and at a next-generation pp -collider [16]. Currently the measurement of di-Higgs physics is suggested to be pursued mainly via:

- Channel 1 [9, 11–15, 17]: $pp \rightarrow hh \rightarrow b\bar{b}\gamma\gamma, b\bar{b}\tau\tau, b\bar{b}WW^*$

which provides the best sensitivity so far in measuring di-Higgs physics, though some preliminary work has also been done on [18]

- Channel 2: $pp \rightarrow jjhh$

(for a recent review, see [19]). The production of both channels however has a negative dependence on $\frac{\lambda}{\lambda_{\text{SM}}}$ in the SM neighborhood, with the differential cross section $\frac{d(\sigma/\sigma_{\text{SM}})}{d(\lambda/\lambda_{\text{SM}})}$ becoming less and less negative as $\frac{\lambda}{\lambda_{\text{SM}}}$ increases [20]. Both effects can suppress their sensitivities in measuring the tri-Higgs coupling, particularly if $\frac{\lambda}{\lambda_{\text{SM}}} > 1$. In addition, in both channels there exists a degeneracy of production cross section with respect to $\frac{\lambda}{\lambda_{\text{SM}}}$. Breaking this degeneracy may further suppress the sensitivities. To explore the di-Higgs physics, therefore, a complementary strategy is needed, particularly in the parameter region with $\frac{\lambda}{\lambda_{\text{SM}}} > 1$.

In this letter we propose a new strategy to explore the di-Higgs physics at pp -colliders, say, via

- Channel 3: $pp \rightarrow t\bar{t}hh$.

The $t\bar{t}hh$ production has a cross section monotonically increasing with respect to $\frac{\lambda}{\lambda_{\text{SM}}}$ [20], with the $\frac{d(\sigma/\sigma_{\text{SM}})}{d(\lambda/\lambda_{\text{SM}})}$ becoming more and more positive as $\frac{\lambda}{\lambda_{\text{SM}}}$ increases [20], which potentially enables it to fulfill our needs. A comparison of the cross sections between the $pp \rightarrow hh$ production and the $pp \rightarrow t\bar{t}hh$ production are provided in Table I. Though its production cross section is an or-

TABLE I: A comparison of the next-to-leading order (NLO) cross sections (in fb) of $t\bar{t}hh$ and hh at pp -colliders [20].

\sqrt{s}	$pp \rightarrow t\bar{t}hh$	$pp \rightarrow hh$
14 TeV	$0.981^{+2.3+2.3\%}_{-9.0-2.8\%}$	$34.8^{+15+2.0\%}_{-14-2.5\%}$
100 TeV	~ 90	~ 1200

der smaller than the $pp \rightarrow hh$ one, the extra $t\bar{t}$ in the $t\bar{t}hh$ events may suppress one order or orders more backgrounds. So, the $t\bar{t}hh$ production opens a new avenue to measure di-Higgs physics at HL-LHC and a next-generation pp -collider, with the decays $hh \rightarrow b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}WW^*$, $b\bar{b}ZZ^*$, etc.

As an illustration, we will focus on the $pp \rightarrow t\bar{t}hh$ production with $hh \rightarrow b\bar{b}b\bar{b}$ at the HL-LHC, which results in a sensitivity comparable to that of the $pp \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$ in searching for the SM di-Higgs production, and shortly discuss its sensitivity at a 100 TeV pp -collider. We would emphasize that this doesn't mean that, for the $t\bar{t}hh$ production, the $hh \rightarrow b\bar{b}b\bar{b}$ has a better sensitivity at a 100 TeV pp -collider, compared to its other decay modes.

ANALYSIS STRATEGY

In the analysis of measuring di-Higgs physics via $pp \rightarrow t\bar{t}hh \rightarrow t\bar{t}b\bar{b}b\bar{b}$ at the HL-LHC, we allow the top pairs to decay either semi-leptonically or leptonically (with $\ell = e, \mu$). Unless indicated explicitly, the discussions below on our strategies can be applied to both cases. In the analyses, the main irreducible backgrounds include

- $pp \rightarrow t\bar{t}b\bar{b}b\bar{b}$,
- $pp \rightarrow t\bar{t}hb\bar{b}, h \rightarrow b\bar{b}$,
- $pp \rightarrow t\bar{t}Zb\bar{b}, Z \rightarrow b\bar{b}$,

and the main reducible backgrounds include

- $pp \rightarrow t\bar{t}b\bar{b}jj$,
- $pp \rightarrow t\bar{t}hjj, h \rightarrow b\bar{b}$,

According to [21], a 70% b -tagging rate at 14 TeV LHC will lead to a 2% mistag rate for light jets and a 24% mistag rate for charm jets, with a 50 pile-up assumed.

Thus only charm jets will be considered for reducible backgrounds. The contributions of $pp \rightarrow t(\bar{t}) + b$ -jets, $W^\pm + b$ -jets, $t\bar{t}hZ$, $t\bar{t}ZZ$ and $t\bar{t}Zjj$ to the backgrounds are negligibly smaller than that of the top-pair plus multi-jets events. So they will not be considered.

Our analysis framework is described in the following. We use MadGraph5 [22] to generate leading-order (LO) signal and background events, with the CTEQ6L1 parton distribution function (PDF) [23] applied. All of the signal and background events are showered by Pythia6.4 [24]. We use DELPHES 3 [25] for detector simulations in which the b -tagging efficiency and the mistag rate of c -jets are tuned to be 70% and 24%, respectively. To reconstruct the Higgs invariant mass, the energy of b -jets is rescaled by a factor

$$1.0 + \frac{p_1}{p_T^{j_b}} + p_2 \quad (1)$$

with $p_1 = 6.15298$, $p_2 = -0.006007$, which is obtained from the $Zb \rightarrow \mu^+\mu^-b$ process.

[Preselection] In the analysis, electrons and muons are isolated by passing the cut

$$|\eta^\ell| < 2.5, I_{iso} < 0.1. \quad (2)$$

Here I_{iso} is energy accumulation (except the energy of the charged target lepton) in a $\Delta R = 0.3$ cone around the charged target lepton which is rescaled by the lepton energy. In the semi-leptonic and di-leptonic top-pair cases, all events are required to contain exactly one isolated charged lepton with $p_T^\ell > 20$ GeV, and exactly two isolated opposite-sign charged leptons with $p_T^\ell > 10$ GeV, respectively.

Jets are reconstructed by using anti- k_T algorithm with $\Delta R = 0.5$ within the $|\eta^j| < 4.5$ region. They are considered for b -tagging if and only if they fall within the tracker acceptance of $|\eta^j| < 2.5$. We require at least 7 jets with $p_T^j > 20$ GeV in the semi-leptonic top-pair case and at least 5 jets with $p_T^j > 20$ GeV in the di-leptonic top-pair case. In addition, we require at least 5 of them be tagged as b -jets. A cut for missing transverse energy $\cancel{E}_T > 30$ GeV is applied in the semi-leptonic top-pair case and the leptonic top-pair case with a pair of charged leptons of the same flavor. In the latter case, we require the di-lepton invariant mass satisfy

$$|m_{\ell\ell} - m_Z| > 10 \text{ GeV}, \quad (3)$$

with $m_Z = 91.1876$ GeV, to suppress the background events which contain a pair of charged leptons due to Z -boson decay. In the leptonic top-pair case with a pair of charged leptons of different flavors (i.e., $e\mu$), no \cancel{E}_T cut and Z mass window cut will be applied.

[Reconstruction of di-Higgs resonances] The two Higgs resonances are reconstructed by using b -jets in each event. Generically there is a combinatorial problem, due

to the fact that top quarks decay into a bottom quark and a W boson. To reconstruct the two Higgs resonances, we choose a combination $((b_1, b_2), (b_3, b_4))$ among the tagged b -jets which gives the minimum of

$$\chi_h \equiv \sqrt{\left(\frac{m_{b_1 b_2} - m_h}{\sigma_h}\right)^2 + \left(\frac{m_{b_3 b_4} - m_h}{\sigma_h}\right)^2}. \quad (4)$$

Here $m_h = 125.4$ GeV and $\sigma_h = 30$ GeV are assumed.

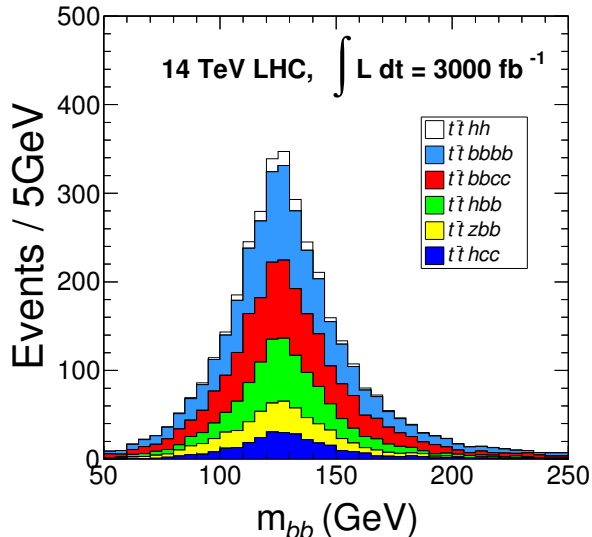


FIG. 1: The m_{bb} reconstruction for the two $b\bar{b}$ pairs which minimize the χ_h in each event after the preselection cut in the semileptonic top-pair case.

All events are required to pass the reconstruction cut of the di-Higgs resonances

$$\chi_h < 1.8. \quad (5)$$

In addition, one of the two selected b -jet pairs may have an invariant mass close to m_h accidentally. In such a case, this cut may lose its effect since the second b -jet pair is allowed to have a relatively large deviation from m_h . To increase the cut efficiency, we require

$$\left(\frac{m_{b_1 b_2} - m_h}{\sigma_h}\right)^2 \text{ and } \left(\frac{m_{b_3 b_4} - m_h}{\sigma_h}\right)^2 \quad (6)$$

be symmetric and neither of them is allowed to be larger than 1.9. As a result, all of the signal and background events surviving of this cut should have two b -jet pairs, with their invariant masses deviating from m_h in a comparable way.

[Reconstruction of top quark resonance] To suppress the backgrounds with no top quarks, we may reconstruct one of the top quarks in the signal events. In semi-leptonic top-pair case, we reconstruct the leptonic top quark by using the charged lepton (ℓ), missing transverse energy (ν) and a reconstructed jet (j). Here the

jet is not necessary to be b -tagged, but it should not be any one among b_1, b_2, b_3 and b_4 . The neutrino momentum along the beam-line direction is solved by using the W -boson mass-shell equation. Due to smearing effects, an imaginary solution is possible. So we require at least one real solution. For the events which have two real solutions, we use both of them to calculate $m_{j\ell\nu}$. Then all events are required to pass a top-mass cut

$$\min|m_{j\ell\nu} - m_t| < 50\text{GeV}, \quad (7)$$

where $m_t = 173.2$ GeV. In spite of this, the cut for top-quark reconstruction might be too aggressive, given that the dominant non-top background W +jets is negligibly small due to the suppression by the requirement of at least seven jets with at least five of them b -tagged in each event. So in the next section, we will present the analysis results, both with and without top-quark reconstruction.

As for the di-leptonic top-pair case, the main non-top backgrounds are Drell-Yan process for the ee and $\mu\mu$ channels, and di-boson+jets for the $e\mu$ channel, which are also sub-dominant. So, no top reconstruction will be applied in the di-leptonic top-pair case.

SIMULATION RESULTS

The cut flows of the signal and the background events in the semi-leptonic top-pair and the di-leptonic top-pair cases are summarized in Table II and Table III, respectively. We find that the background contributed by faked c -jets is important and hence is not negligible. The cut flows indicate that a statistical significance as large as $S/\sqrt{B} = 2.0\sigma$ (no top-quark reconstruction) and $S/\sqrt{B} = 1.5\sigma$ (with top-quark reconstruction) can be achieved in the semi-leptonic top-pair case. As for the di-leptonic top-pair case, the statistical significance is $S/\sqrt{B} = 0.8\sigma$ at the HL-LHC. The sensitivities in these two analyses can be combined quadratically, which gives a sensitivity of 2.2σ (no top-quark reconstruction), in comparison to a statistical significance of 2.3σ expected to be achieved at the HL-LHC via $pp \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$, with a 75% b -tagging efficiency assumed [16].

TABLE II: Cut flows of searching for $t\bar{t}hh \rightarrow t\bar{t}b\bar{b}b\bar{b}$ at the HL-LHC via the semi-leptonic top-pair channel. The unit used in the table is attobarn.

$\sqrt{s} = 14$ TeV	$t\bar{t}hh$	$t\bar{t}b\bar{b}b\bar{b}$	$t\bar{t}b\bar{b}c\bar{c}$	$t\bar{t}h\bar{b}\bar{b}$	$t\bar{t}Zb\bar{b}$	$t\bar{t}hc\bar{c}$
Preselection	39.0	390.6	353.1	222.7	126.8	98.2
Di-Higgs rec.	33.0	269.3	242.1	171.0	93.5	76.8
Top rec.	19.5	160.7	149.0	102.8	54.6	47.1

TABLE III: Cut flows of searching for $t\bar{t}hh \rightarrow t\bar{t}b\bar{b}b\bar{b}$ at the HL-LHC via the dileptonic top-pair channel. The unit used in the table is attobarn.

$\sqrt{s} = 14$ TeV	$t\bar{t}hh$	$t\bar{t}b\bar{b}b\bar{b}$	$t\bar{t}b\bar{b}c\bar{c}$	$t\bar{t}h\bar{b}\bar{b}$	$t\bar{t}Zb\bar{b}$	$t\bar{t}hc\bar{c}$
Preselection	4.8	41.6	30.6	22.6	9.7	8.1
Di-Higgs rec.	4.1	27.1	20.7	16.8	7.4	6.4

DISCUSSIONS

Leading-order discussions have been pursued, regarding the measurement of di-Higgs physics via the $t\bar{t}hh$ channel. In the illustrational case with $pp \rightarrow t\bar{t}hh \rightarrow t\bar{t}b\bar{b}b\bar{b}$, we show that a sensitivity comparable to that of the $pp \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$ channel is achievable in searching for the SM di-Higgs production at the HL-LHC, which is very encouraging. However, we need to note that the dominant backgrounds in this case are $t\bar{t}b\bar{b}b\bar{b}$ and $t\bar{t}b\bar{b}jj$, both of which have a cross section of order α_S^6 at tree level. This may lead to a large theoretical uncertainty in estimating the backgrounds. A calculation of higher-order corrections therefore is important for suppressing this uncertainty. Alternatively, a data-driven method may help in this regard.

At analysis level, a further improvement is certainly possible. For example, we may introduce color-flow variables such as the “pull angle” of b -jet pairs [26] to reconstruct the di-Higgs resonances, which has been shown to be useful in suppressing combinatorial backgrounds of multiple b -jets in both supersymmetric [27] and non-supersymmetric [28] contexts. In addition, we can apply more advanced analysis tools, such as the tool of jet-substructure and the multivariate method of Boost Decision Tree, which have been successfully applied for measuring di-Higgs physics in the channels $pp \rightarrow hh \rightarrow b\bar{b}\tau\tau$ [9] and $b\bar{b}WW$ [14], respectively.

More importantly, the $pp \rightarrow t\bar{t}hh$ provides a series of new opportunities to study di-Higgs physics at a next-generation pp -collider, with the decays $hh \rightarrow b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}WW^*$, $b\bar{b}ZZ^*$, etc. Though its production cross section is an order smaller than that of $pp \rightarrow hh$, the extra $t\bar{t}$ in the $t\bar{t}hh$ events may suppress one order or orders more backgrounds. As an illustration, let’s consider the specific process $pp \rightarrow t\bar{t}hh \rightarrow t\bar{t}b\bar{b}b\bar{b}$ again at a 100 TeV pp -collider, with $t\bar{t}$ decaying semi-leptonically. Note, this doesn’t mean that it has a better sensitivity compared to the other hh decay modes in the $pp \rightarrow t\bar{t}hh$ production. In this case, we modify the p_T cuts for jets to be $p_T^j > 40$ GeV and the \cancel{E}_T cut to be $\cancel{E}_T > 50$ GeV, and require at least one jet with its p_T greater than 100 GeV and at least one b -jet with its p_T greater than 120 GeV. To

reconstruct the di-Higgs resonances, we redefine χ_h to be

$$\chi_h \equiv \left[\left(\frac{m_{b_1 b_2} - m_h}{\sigma_h} \right)^p + \left(\frac{m_{b_3 b_4} - m_h}{\sigma_h} \right)^p \right]^{1/p}. \quad (8)$$

We require the combination of b -jet pairs with the minimal χ_h satisfy $\chi_h < 2.5$ for $p = 1.5$ and $\chi_h > 1.5$ for $p = 0.2$. The latter is applied to avoid accidental “di-Higgs” resonances in the backgrounds. In addition, we require the di-Higgs invariant mass $m_{hh} < 750$ GeV, and $(|\Delta R_{b_1 b_2}|^p - |\Delta R_{b_3 b_4}|^p)^{1/p} < 0.1$ for $p = 0.3$. The cut flows of both the signal and backgrounds are present in Table IV, which indicate a statistical significances $S/\sqrt{B} = 4.9\sigma$ (no top-quark reconstruction) and 3.3σ (with top-quark reconstruction) for $3ab^{-1}$ of data.

TABLE IV: Cut flows of searching for $pp \rightarrow t\bar{t}hh \rightarrow t\bar{t}b\bar{b}b\bar{b}$ at the 100 TeV pp -collider via the semi-leptonic top-pair channel. The unit used in the table is attobarn.

$\sqrt{s} = 100$ TeV	$t\bar{t}hh$	$t\bar{t}b\bar{b}b\bar{b}$	$t\bar{t}b\bar{b}c\bar{c}$	$t\bar{t}h\bar{b}\bar{b}$	$t\bar{t}Zb\bar{b}$	$t\bar{t}hc\bar{c}$
Preselection	830.5	72678.7	13322.6	10231.8	3252.0	1995.7
Di-Higgs rec.	608.4	31679.7	6285.2	5689.9	1504.0	1193.3
Top rec.	240.1	10384.4	2189.1	2208.6	428.0	384.9

One application of the di-Higgs measurement is to probe the tri-Higgs coupling. A rough estimation based on the calculation in [20] gives

$$\left. \frac{d(\sigma/\sigma_{SM})}{d(\lambda/\lambda_{SM})} \right|_{\frac{\lambda}{\lambda_{SM}}=1} \sim 0.3 \quad (9)$$

for the $pp \rightarrow t\bar{t}hh$ production, in comparison to its value ~ -0.8 for the $pp \rightarrow hh$ production [16], at a 14 TeV pp -collider. According to the analyses above, the SM tri-Higgs coupling can be measured with a statistical accuracy of $\sim 150\%$ at the HL-LHC, and of $\sim 70\%$ at a 100 TeV pp -collider with $3ab^{-1}$ of data (with the relation in Eq. (9) assumed), via the channel $pp \rightarrow t\bar{t}hh \rightarrow t\bar{t}b\bar{b}b\bar{b}$. Here the former is based on a combination of the semi-leptonic and leptonic $t\bar{t}$ decay modes, and the latter is based on the semi-leptonic one only. Though the accuracy of this measurement is lower than what can be achieved at the HL-LHC via the $pp \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$ channel, say, $\sim 50\%$ [16], we are able to use it to preliminarily probe the $\frac{\lambda}{\lambda_{SM}}$ shift required for generating strong enough first-order EWPT in the early Universe [1].

The story could be more subtle if $\frac{\lambda}{\lambda_{SM}} > 1$. Different from the $pp \rightarrow hh$ (similar for the $pp \rightarrow jjhh$) production whose cross section negatively depends on $\frac{\lambda}{\lambda_{SM}}$ in the SM neighborhood, the $pp \rightarrow t\bar{t}hh$ production has a cross section monotonically increasing with respect to $\frac{\lambda}{\lambda_{SM}}$. Any positive shift in $\frac{\lambda}{\lambda_{SM}}$ caused by new physics, such as the operator $\frac{|H|^6}{\Lambda^2}$ used for strengthening the EWPT

in the early Universe [1], will lead to a suppression of the $pp \rightarrow hh$ production, and simultaneously an enhancement of the $pp \rightarrow t\bar{t}hh$ one, in this neighborhood. Meanwhile, the $\left| \frac{d(\sigma/\sigma_{\text{SM}})}{d(\lambda/\lambda_{\text{SM}})} \right|$ becomes smaller for the $pp \rightarrow hh$ production and larger for the $pp \rightarrow t\bar{t}hh$ production as $\frac{\lambda}{\lambda_{\text{SM}}}$ increases, which also leads to a suppression for the $pp \rightarrow hh$ sensitivity, and a simultaneous enhancement of the $pp \rightarrow t\bar{t}hh$ sensitivity, in measuring the tri-Higgs coupling. For example [20], with a shift 0.5 in $\frac{\lambda}{\lambda_{\text{SM}}}$, the $pp \rightarrow t\bar{t}hh$ production is enhanced by twice, relative to the $pp \rightarrow hh$ one, while the $\left| \frac{d(\sigma/\sigma_{\text{SM}})}{d(\lambda/\lambda_{\text{SM}})} \right|$ becomes comparable for both. This leads to a $pp \rightarrow t\bar{t}hh \rightarrow t\bar{t}b\bar{b}b\bar{b}$ sensitivity roughly twice better than the $pp \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$ one in measuring the tri-Higgs coupling at the HL-LHC. Even worse, there exists a degeneracy of cross section with respect to $\frac{\lambda}{\lambda_{\text{SM}}}$ for the $pp \rightarrow hh$ production [20]. Breaking this degeneracy may further suppress its sensitivity. Given these considerations, the $pp \rightarrow t\bar{t}hh$ production may play a crucial role in measuring the tri-Higgs coupling and hence in exploring the CBA puzzle.

Another application of the di-Higgs measurement is to search for new physics coupling with the Higgs field directly. The $t\bar{t}hh$ (including $t\bar{t}hh + \cancel{E}_T$) production extensively exists in the scenarios of new physics. For example, it can be initiated by the pair production of top partners, in both supersymmetric (e.g., see [27]) and non-supersymmetric (e.g., see [28]) contexts. In addition, higher dimensional operators in low-energy effective theories may modify the $pp \rightarrow t\bar{t}hh$ production. $\frac{t\bar{t}hh}{\Lambda}$ is such an example which can contribute via top-quark pair production [4–6]. However, to achieve the double goals of measuring the tri-Higgs coupling and searching for new physics coupling with the Higgs field simultaneously, the $pp \rightarrow t\bar{t}hh$ events need to be disentangled.

Based on the leading-order discussions above, we conclude that the $pp \rightarrow t\bar{t}hh$ channel opens a new avenue to measure di-Higgs physics, complementary to the channels $pp \rightarrow hh, jjhh$ suggested in the past, at both the HL-LHC and a next-generation pp -collider. A systematical exploration along this line is definitely required, which we will leave to a future work.

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